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Antimatter in Different Baryogenesis Scenarios

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Abstract

Possible mechanisms of abundant creation of antimatter in the universe are reviewed. The necessary conditions for that are: baryonic charge nonconservation, spontaneous breaking of charge symmetry or nonequilibrium initial state, and the formation of appropriate initial conditions during inflation. In this case the universe may be populated with domains, cells, or even stellar size objects consisting of antimatter.

1 Introduction

The problem that I am going to discuss is not directly related to the subject of this conference dedicated to experimental search of baryon nonconservation. Still there is one thing in common, all models of cosmological creation of antimatter request nonconservation of baryonic charge. There may be of course a production of antibaryons by e.g. decays or annihilation of new long-lived heavy particles (like quasistable neutralinos of supersymmetric models) which may proceed with baryonic charge conservation or even production of antinucleons by energetic cosmic rays but this is not what is usually understood as creation of antimatter.

We know from observations that the universe in our neighborhood is 100% charge asymmetric. There are only baryons and electrons and no their antiparticles in a comparable amount. Though the asymmetry is large now, in some sense it is very small. The number density of baryons, N_B , relative the number density of photons in the cosmic microwave background radiation, N_γ is:

$$N_B/N_\gamma \approx 3 \times 10^{-10 \pm 0.3}, \quad (1)$$

This means that the universe was almost charge symmetric at high temperatures, $T > (a\ few) \times 100$ MeV. At these temperatures the excess of baryonic charge was approximately one unit per 10^9 baryons. Still though the ratio (1) is very small, it is 9 orders of magnitude larger than it would be in the case of locally charge symmetric universe. We do not know if all the universe is charge asymmetric with the same universal magnitude of the charge asymmetry or the charge asymmetry is point dependent and can even change its sign. Nothing is known about the size of these locally asymmetric domains, l_B . Existing data indicate that $l_B > 10$ Mpc.

Whether l_B is above or below the present day horizon, $l_h = 10$ Gpc, is an intriguing question and in what follows I will discuss the models which predict a relatively small value of l_B , so that antimatter may be accessible to observations.

It is very important for all these models as well as for the planned experiments on search of baryon nonconservation to know if baryonic charge is indeed nonconserved. At the present time cosmology gives the only "experimental" and a very strong argument in favor of nonconservation of baryons. In other words our existence strongly implies baryon nonconservation. This is not just that the baryon asymmetry of the universe can be generated only if baryonic charge is nonconserved as was suggested 25 years ago by Sakharov [1]. (For possible but rather exotic exceptions see review paper [2].) There is something more, namely that sufficiently long inflation could not go with conserved baryonic charge [3, 2]. Since it seems that without inflation is impossible to make a suitable for life universe we have to assume that baryons are indeed nonconserved. The argument goes as follows. For successful solution of cosmological problems[4] inflationary stage should last sufficiently long (for a review see e.g. books [5, 3]). The duration of inflation τ should be larger than 60 Hubble times, $H_I \tau > 60$, where H_I is the Hubble constant during inflation such that the scale factor, which describes the universe expansion, behaves as $a(t) \sim \exp(H_I t)$. One may say that in order to create the observed number density of baryons, the initial baryonic charge density at the onset of inflation should be unnaturally large, at least $e^{180}(T_{Rh}/2.7K)^3$ times larger than at the present day. Here 2.7K is the temperature of the cosmic microwave background radiation today and T_{Rh} is the temperature at the end of inflation. Such a large number is of course not natural but it does not mean impossible. What makes inflation with conserved baryons impossible is the energy density considerations. The Hubble parameter is expressed through the cosmological energy density ρ as $H = \sqrt{8\pi\rho/3m_{Pl}^2}$. To make an exponential expansion the parameter H must be approximately constant. It implies that in this regime the energy density does not change with the expansion but remains constant too. It is indeed realized in models where inflation is driven by a scalar (inflaton) field. Let us assume now that baryons are conserved. In accordance with eq.(1) the energy density associated with baryonic charge at the hot early stage of the universe evolution is about $10^{-10} - 10^{-9}$ of the total energy density. Let us go backward in time to even earlier period, when inflation took place. At this stage the energy density of all forms of matter is represented by the inflaton and remains constant in the course of contraction (remember we are going backward in time). However the energy density associated with baryonic charge cannot be constant because by assumption this charge is conserved. Correspondingly it changes with the scale factor as $\rho_B \sim a^{-4}$. It means that in less than 6 Hubble times the energy density of baryons becomes dominant and the total energy density could not remain constant. Thus with conserved baryons inflation can be only very short, $H_I \tau \leq 6$, which is by far below the necessary duration.

Thus we must conclude that baryonic charge in our universe is not conserved and the direct experimental search of the proton instability or neutron-antineutron oscillations is not only just experiments for putting an upper bound but the experiments for discovery really existing phenomenon. Unfortunately cosmology does not say anything about the magnitude of the effect. It very much depends upon the mechanism of baryonic charge nonconservation and one should keep in mind that the mechanism through which the observed baryon asymmetry of the universe has been created is not necessarily the same that leads to the proton decay or neutron-antineutron oscillations. Theory opens several possibilities to break B-conservation with different levels of creditability. The standard $SU(2) \times U(1)$ -electroweak interactions are known to break baryonic current conservation by the chiral quantum anomaly[6]. This is a rather strong theoretical prediction but unfortunately manifestations of this phenomenon in low energy physics are extremely weak, they are suppressed by the

tunnel penetration factor $\exp(4\pi \sin^2 \theta_W / \alpha) \approx 10^{-170}$. At high temperatures the effect may be grossly amplified and may explain the observed baryon asymmetry of the universe[7] (for the reviews see the talk by A. Cohen at this Conference or review papers[2, 8]). Fortunately there are plenty of other mechanisms of B-nonconservation, which do not necessarily operate at ultrahigh energies, as for example the GUT's one does. Some of them are so efficient at low energies that the direct observation of the effect is almost at hand and, as M. Goldhaber said at the beginning of this meeting, one should rush to the laboratory and to make the discovery (unfortunately he referred to the unsuccessful attempts to find proton decay in the first generation experiments). Let us hope that the second generation will make it.

2 General conditions for cosmological creation of antimatter.

Why at all may we expect that there are macroscopically large domains of antimatter in the universe? There is no rigorous theory which requests that. Moreover in all simple models of baryogenesis the baryon asymmetry is a universal constant over all the universe so that there is no place for antimatter. On the other hand simple modifications of baryogenesis scenarios will result in formation of domains with different signs of baryon asymmetry. To this end the following two conditions should be satisfied:

1. Different signs of C and CP-violation in different space points.
2. Inflationary (but moderate) blow-up of regions with different signs of charge symmetry breaking.

The first condition is realized in the model of spontaneous breaking of charge symmetry[9]. It is assumed that the Lagrangian is charge symmetric but the ground state is not. It can be realized by a complex scalar field which acquires a nonzero vacuum expectation value like the one in the usual Higgs mechanism. The effective potential of this field may e.g. have the form:

$$U(\phi) = -m^2|\phi|^2 + \lambda(\phi^4 + \phi^{*4}) + g^2 T^2 |\phi|^2 \quad (2)$$

where the last term came from the temperature corrections, which force the system to the symmetric state at high temperatures[10]. At low temperatures the state $\langle \phi \rangle = 0$ becomes energetically unfavorable and a complex condensate is developed which through Yukawa coupling would give rise to breaking of C and CP by e.g. complex fermion masses. One can see that through this mechanism domains with opposite signs of C(CP)-odd phase are indeed formed. In these domains either matter or antimatter is generated by baryogenesis[11]. The universe in this model is charge symmetric on the average and asymmetric locally.

There are two serious problems which this model encounters. First is that the average size of the domains is too small. If they are formed in the second order phase transition, their size at the moment of formation is determined by the so called Ginzburg temperature and is approximately equal to $l_i = 1/(\lambda T_c)$ where T_c is the critical temperature at which the phase transition takes place and λ is the selfinteraction coupling constant. In this case different domains would expand together with the universe and now their size would reach $l_0 = l_i(T_c/T_0) = 1/(\lambda T_0)$ where $T_0 = 2.7\text{K}$ is the present day temperature of the background radiation. If the phase transition is

first order then the bubbles of the broken phase are formed in the symmetric background. In this case different bubbles initially are not in contact with each other, typically the distance between them is much larger than their size, and their walls may expand faster than the universe, even as fast as the speed of light. Thus to the moment when the phase transition is completed the typical size of the bubbles may be as large as the horizon, $l_f \approx t \approx m_{Pl}/T_f^2$. After that they are stretched out by the factor T_f/T_0 due to the universe expansion. To make the present day size around (or larger than) 10 Mpc we need $T_f \sim 100$ eV. It is difficult (if possible) to arrange that without distorting successful results of the standard cosmology. Thus to make observationally acceptable size of the matter-antimatter domains, a superluminous cosmological expansion seems necessary. This solution was proposed in ref.[12] where exponential (inflationary) expansion was assumed. With this expansion law it is quite easy to overfulfill the plan and to inflate the domains above the present day horizon. Effectively it would mean a return to the old charge asymmetric universe without any visible antimatter. So some fine-tuning is necessary which would permit to make the domain size above 10 Mpc and below 10 Gpc.

The second cosmological problem which may arise in this model is a very high energy density and/or large inhomogeneity created by the domain walls[13]. This can be resolved if domain walls were destroyed at later stage by the symmetry restoration at low temperature or by some other mechanism [14, 15]. However there could be scenarios of baryogenesis in which domains of matter-antimatter may be created without domain walls. The basic idea of these scenarios is that baryogenesis proceeds when the (scalar) field which creates C(CP)-breaking or stores baryonic charge is not in the dynamically equilibrium state. These models are described in more detail in the following sections.

3 Antimatter in models with baryonic charge condensate.

In supersymmetric theories there exist scalar fields with nonzero baryonic charge, superpartners of quarks. Such fields (more exactly the electrically neutral colorless combination of squarks and sleptons) may form a classical condensate in the early universe, in particular at inflationary stage, if there are the so called flat directions in the potentials. Subsequent decay of this condensate would result in a considerable baryon asymmetry[16]. The picture can be visualized as follows. Evolution of a complex spatially homogeneous scalar field is described by the same equation as two-dimensional motion of a point-like body in the same potential $U(Re\phi, Im\phi) \rightarrow U(x, y)$. Baryonic charge density is equivalent in this language to the angular momentum of the mechanical motion of the body. The potential typically has the form of eq.(2). It is spherically symmetric at small ϕ and asymmetric and has flat directions at large ϕ . So for small values of the amplitude of ϕ baryonic charge is conserved while evolution of ϕ with a large amplitude goes with a strong baryonic charge nonconservation. If the mass of ϕ is smaller than the Hubble parameter during inflation, the field would climb up the potential slope due to infrared instability of scalar fields in De Sitter space-time[17, 18, 19]. When inflation ends the field ϕ would evolve down to the equilibrium value. Depending upon the initial conditions it may rotate clock-wise or anticlock-wise near the origin or in other words it would produce baryons or antibaryons in its decay. One sees at this example that even in the charge symmetric theory baryon asymmetry may evolve; charge asymmetry is created by asymmetric initial conditions which in turn are created by rising quantum fluctuations of the scalar baryonic field during inflationary stage. Of course at large scales the universe is charge symmetric.

It is evident that there is no domain wall problem in this scenario. The characteristic size of domain with a definite sign of baryonic charge was estimated in ref.[2]. At the end of inflation it is equal to $L_{Bi} = H_I^{-1} \exp(\lambda^{-1/2})$. With λ around $10^{-3} - 10^{-4}$ such domains would be consistent with observations and still inside the present day horizon. Since it is natural to assume that the baryon asymmetry in this model gradually changes from a positive value through zero to a negative one, the annihilation at the boundaries of the domains would be much weaker than in the (usually assumed) picture of interactions of domains with sharp boundaries. Correspondingly the limits on the magnitude of l_B would be considerably weaker. Note that not only the sign but also the magnitude of the baryon asymmetry in different domains in this scenario may be significantly different.

4 Alternating (and periodic?) matter-antimatter cosmic layers.

A relatively simple modifications of the baryogenesis scenario would permit to get a very interesting distribution of matter and antimatter in the universe ranging from strictly periodic flat alternating layers of matter and antimatter[20, 21, 22, 23] to cell structures with each cell formed by matter or antimatter with an average characteristic size which could easily be around 100 Mpc. The basic assumptions leading to this kind of structure are quite simple and even natural. Assume that there exists a complex scalar field ϕ with the mass which is smaller than the Hubble parameter at inflation, $m_\phi < H_I$. Assume also that the potential $U(\phi)$ contains nonharmonic terms (i.e. not only $m^2|\phi|^2$ but also e.g. $\lambda|\phi|^4$). Assume at last that a condensate $\langle\phi\rangle = \sigma(\vec{r})$ was formed during inflation. It is essential that the condensate σ is not a constant but a slowly varying function of \vec{r} . Such a condensate could be formed due to infrared instability of the scalar field mentioned in the previous section or in first order phase transition with very much inflated bubble walls. The characteristic scale at which ϕ essentially varies, l_ϕ , may be exponentially large due to inflation.

When inflation is over, the field ϕ relaxes down to its equilibrium value, oscillating near the minimum of the potential. If baryogenesis takes place very soon after the end of the inflation and the rate of the baryogenesis is large in comparison with the frequency of oscillations of ϕ , then the instant value of the amplitude of ϕ would be imprinted on the magnitude of the asymmetry because, as we mentioned above, a condensate of a complex scalar field gives rise to C(CP)-violation proportional to the field amplitude. Thus baryogenesis makes a snapshot of the magnitude of ϕ . Now since the potential $U(\phi)$ is not harmonic, the frequency of the oscillations of ϕ depends on the amplitude. By assumption the initial amplitude is not the same at different space points and so the frequency is also a function of \vec{r} . Because of that the initially smooth function $\phi(\vec{r})$ would turn into an oscillating one with a huge wave length of oscillations proportional to l_ϕ .

If ϕ oscillates around zero than its snapshot would show both positive and negative values. In the case that there are no other comparable sources of C(CP)-violation this model would produce approximately equal number of baryons and antibaryons situated on relatively thin layers or shells. If the equilibrium value of ϕ is nonzero or there is an explicit charge symmetry breaking, matter or antimatter would be produced more efficiently and the universe on the average would be more baryonic or antibaryonic.

5 Island universe model.

It is relatively simple to construct a cosmological model of the universe consisting of separate baryonic or antibaryonic islands floating in the sea of invisible matter or even of a baryonic island surrounded by the sea of antimatter[20, 21]. In the first case our chances to observe antimatter are minor because the distance between the islands is typically rather large and the probability of the collisions is low. In the second case antimatter may be possibly observed by the gamma ray background.

In short the scenario leading to the insular structure can be realized as follows. First, the charge symmetry should be spontaneously broken and the phase transition to the CP-odd phase should be first order with supercooling and formation of bubbles of the new phase inside the quasistable CP-symmetric phase. Second, there should be sufficiently long period of exponential expansion after the phase transition but not too long. Otherwise the sizes of the CP-odd bubbles would be either too small in contradiction with observations or too large so that we would never see the boundary. If the phase transition took place before the end of inflation but not far from it, the island size could be of the order of the present horizon size but still slightly smaller than the latter. When inflation ends and the Universe is (re)heated an excess of particles over antiparticles or vice versa is generated inside of the bubble by the normal process of baryogenesis. Outside of the bubbles where the charge symmetry is unbroken the baryonic charge density would be equal to zero. However it might be that there are two mechanisms of C(CP)-breaking, the spontaneous one operating inside the island and an explicit one operating everywhere. In that case the baryogenesis would proceed also outside the bubbles and may have either sign, in particular it is possible that the baryonic island would be in the antibaryonic sea. In that case one may expect a noticeable annihilation on the coast.

The size of the islands (or bubbles) depends upon the duration of inflation after the phase transition to C(CP)-odd phase took place. Normally the duration of inflation is very large in comparison with the minimal necessary one, $H_I \tau \approx 60$, and one would naturally expect that the size would be much larger than the present day horizon. To escape this conclusion one may introduce a coupling of the field ϕ , which creates charge symmetry breaking, to the inflaton field Φ , e.g. of the form:

$$L_{int} = \lambda' |\phi|^2 (\Phi - \Phi_1)^2 \quad (3)$$

with $\lambda' > 0$ and Φ_1 is such that the inflaton field reaches and passes this value in the course of inflation. This interaction leads to effective time dependent mass of ϕ , $\Delta m^2(t) = \lambda' [\Phi(t) - \Phi_1]^2$, so that the state $\phi = 0$ is almost always classically stable with respect to small fluctuations and only when Φ is close to Φ_1 there is a period of instability. Quantum fluctuations of ϕ at that time increases and, if they exceed a critical value ϕ_c to the moment when the condition of stability becomes valid again, they do not return to the false vacuum state but would rise up to a nonzero complex value. Thus the bubbles of CP-odd vacuum can be formed. The average bubble size d and the distance l between them are very much model dependent. In particular the value of l can vary from 0 to infinity and correspondingly vary the odds for observing antimatter in such universe.

6 Very inhomogeneous baryogenesis.

The model considered in this section combines some of the ideas discussed above but in an extremal form. Namely the mechanism of baryogenesis was proposed[24] which creates a huge baryon asymmetry $N_B/N_\gamma = O(1)$ in relatively small regions with, say, stellar size over the normal homogeneous baryonic background with N_B/N_γ given by

eq.(1). The probability of production of such high-B regions should be sufficiently small so that their number density is below the observational bounds. The sign of the baryon asymmetry in these regions is with equal probability positive or negative so we can expect both high density and small size baryonic and antibaryonic objects. There is no observational difference between the two if the density is so high that those objects collapsed at some early epoch into compact stellar remnants and black holes. This model presents a mechanism for early black hole formation from large amplitude isothermal fluctuations at small spatial scales. In this case, at least some dark matter in the universe would be in the form of baryonic (and antibaryonic) black holes. Smaller uncollapsed bubbles of antibaryonic matter would be observable either as point-like sources of γ -radiation or, if they annihilated earlier, as some bright spots in the otherwise isotropic background radiation. If the number density of these objects were sufficiently high, early $p\bar{p}$ -annihilation could result in the distortion of the spectrum of background radiation. Unfortunately there is too much freedom in the model to make any specific predictions. The amount of uncollapsed antimatter may vary from an unnoticeable amount to that in contradiction with existing data.

The basic idea of the model is to make the conditions in which the Affleck-Dine[16] mechanism of baryogenesis could be operative only in small spatial regions. In these regions the asymmetry may be huge since this mechanism suffers from overabundant baryoproduction in contrast to all other ones. This could be realized if the flat directions in the potential of the scalar baryonic field ϕ are separated from the origin (where the field is normally located) by a potential barrier. In this case the jump to the flat directions could be achieved only through the tunnel transition which is usually strongly suppressed. This ensures the desired suppression of the production of high B-bubbles. Once again the jump to the flat directions should be done during inflationary stage to make the bubbles macroscopically large at the present time. The necessary tuning may be achieved by a coupling between ϕ and the inflaton field.

Under reasonable assumptions about the production mechanism the mass distribution of the high density baryonic or antibaryonic bubbles is given by the expression[24]:

$$\frac{dn}{dM} = M_0^4 \exp[-\alpha - \beta \ln^2(M/M_0)] \quad (4)$$

The constants α , β , and M_0 are determined by the parameters of the potential of the ϕ -field and the Hubble constant during inflation. With the reasonable choice of the parameters it is possible to get M_0 in the interesting interval $(1 - 10^6)M_\odot$ where M_\odot is the solar mass.

The cosmological evolution of such bubbles depends upon their size and the magnitude of the baryon asymmetry or, to be more precise, upon the ratio of their size, l_B and the Jeans wave length, λ_J . Bubbles of large size, $l_B > \lambda_J$, would form compact objects, either stars or black holes, at a very early stage of the evolution of the universe. Stars of antimatter could emit considerable energy due to annihilation of the accreted matter. With a sufficiently large amount of surrounding matter, they should radiate at their Eddington limit,

$$L_{Ed} = 3 \cdot 10^4 L_\odot \left(\frac{M}{M_\odot} \right) \quad (5)$$

where $L_\odot \approx 4 \cdot 10^{33}$ erg/sec is the solar luminosity. The life-time of such objects is of the order of $5 \cdot 10^9$ years. If the accretion rate is below the limiting one (e.g. due to the surrounding deficit of matter), the luminosities would be smaller and the life-times would be larger. Those objects can be observed as γ -ray sources isotropically distributed over the sky. A very interesting phenomena may take place in a collision of the antistar with a normal star. One would expect to observe together with a flux of gamma radiation rare events of antinuclei, in particular anti-helium-4.

7 Conclusion.

One cannot make any strong conclusion from this very speculative talk. What seems quite definite is that baryonic charge is not conserved. Hence proton is in principle unstable, neutron-antineutron oscillations should exist and this is matter of "only" good luck to observe them in direct laboratory experiments. Unfortunately cosmology is absolutely helpless in predicting the magnitude of the effects.

The probability of observing big lumps of antimatter in the universe suffers from the similar uncertainty. The difference is however that in this case the existence of antimatter is by no means obligatory. While baryonic charge is definitely nonconserved, the universe may still contain only baryons. Another sad but very probable option is that the universe may be charge symmetric but antimatter is far beyond present day horizon. It means effectively that "our best of all possible worlds" does not contain antimatter. Unfortunately the models with inflationary expansion of the matter-antimatter bubbles would quite easily overexpand them too far. Still a rather simple coupling of the underlying scalar fields to the inflaton may stop inflating the bubbles at sufficiently early moment and make them comfortably (for possible observations) nearby. If this is true, very interesting configurations of matter-antimatter regions in the universe are possible, as it has been discussed above. Anyhow independently of theoretical speculations the idea of the charge symmetric universe looks so interesting and attractive that the searches for that just cannot be unsuccessful.

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References

- [1] A. D. Sakharov, Pis'ma Zh. Eksp. Teor. Fiz. **5** 32 (1967).
- [2] A.D. Dolgov, Phys. Repts. **222**, 311 (1992).
- [3] A.D. Dolgov, M.V. Sazhin and Ya.B. Zeldovich, Basics of Modern Cosmology. Editions Frontiers. France, 1990.
- [4] A. Guth, Phys. Rev. **D23** 347 (1981).
- [5] A.D. Linde, Particle Physics and Inflationary Cosmology. Harwood Academic Publishers, 1990.
- [6] G. t'Hooft, Phys. Rev. Lett. **37**, 8 (1976); Phys. Rev. **D14**, 343 (1976).
- [7] V.A. Kuzmin, V.A. Rubakov, and M.E. Shaposhnikov, Phys. Lett. **B191**, 171 (1987).
- [8] Cohen, A.G., D. B. Kaplan, and A. E. Nelson, Annu. Rev. Nucl. Part. Sci. **43** (1993).
- [9] T.D. Lee, Phys. Rev. **D8**, 1226 (1973).
- [10] D.A. Kirzhnits, Pis'ma ZhETF, **15**, 745 (1972)(for the review see e.g. A.D. Linde, Repts. Prog. Phys. **42**, 389 (1979)).
- [11] R.W. Brown and F.W. Stecker, Phys. Rev. Lett. **43**, 315 (1979).

- [12] K. Sato, Phys. Lett. **99B**, 66 (1981).
- [13] Ya.B. Zel'dovich, I.Yu. Kobzarev, and L.B. Okun, ZhETF **67**, 3 (1974).
- [14] R.N. Mohapatra and G. Senjanović, Phys. Rev. **D20**, 3390 (1979); Phys. Rev. Lett. **42**, 1651 (1979).
- [15] V.A. Kuzmin, I.I. Tkachev, and M.E. Shaposhnikov, Phys. Lett. **105B**, 167 (1981).
- [16] I. Affleck and M. Dine, Nucl. Phys. **B249**, 361 (1985).
- [17] T.S. Bunch and P.C.W. Davies, Proc. Roy. Soc.(London), **A360**, 117 (1978).
- [18] A.D. Linde, Phys. Lett. **116B**, 335 (1982).
- [19] A. Vilenkin and L.H. Ford, Phys. Rev. **D26**, 1231 (1982).
- [20] A.D. Dolgov, and N.S. Kardashev, Space Research Int. Preprint-1190 (1986).
- [21] A.D. Dolgov, A.F. Illarionov, N.S. Kardashev, and I.D. Novikov, ZhETF. **94**, 1 (1987).
- [22] M.V. Chizhov and A.D. Dolgov, Nucl. Phys. **B372**, 521 (1992).
- [23] M. Chizhov and D. Kirilova, Preprint ICTP IC/95/172.
- [24] A. Dolgov and J. Silk, Phys. Rev., **D47**, 4244 (1993).